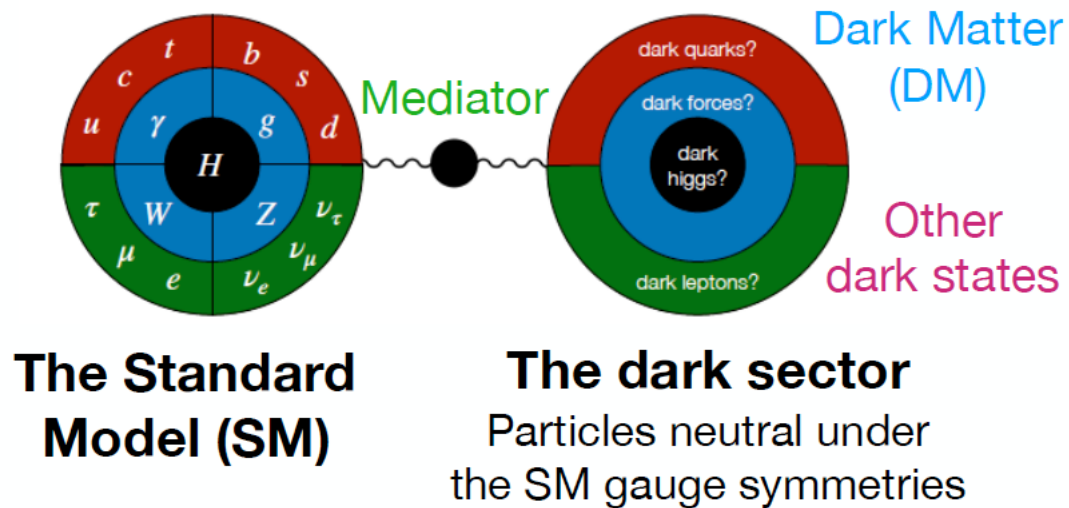
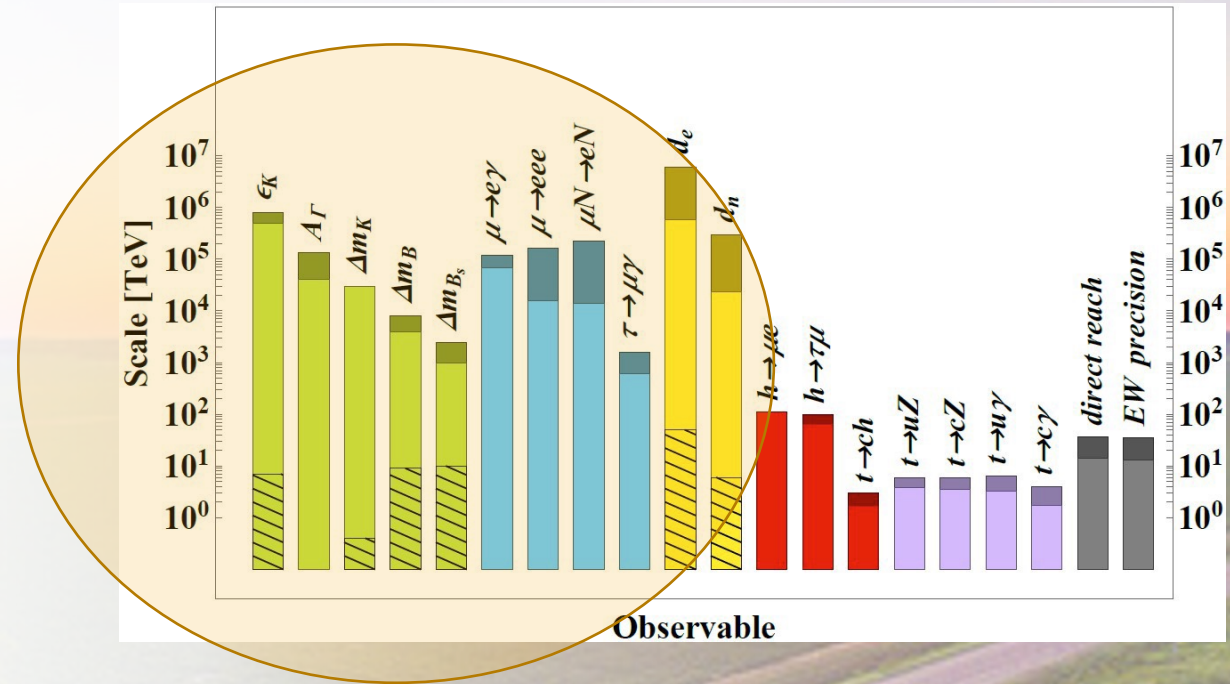
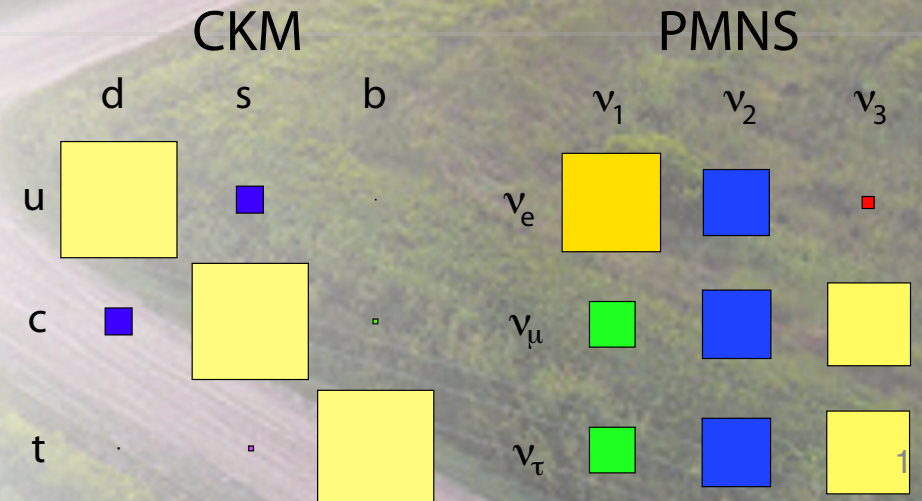


The Rare processes and Precision measurements (RPF) frontier

A crossroad for the next HEP physics landscape



Quark mixing versus ν mixing



The team

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Apologies for the
incomplete
acknowledgement of
their work!

Thanks to the many
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contributors!

The big picture

- ❑ Develop and sustain diverse an experimental program well-motivated by the P5 science driver **Explore the unknown: new particles, interactions, and physical principles**, with connections to the energy and neutrino frontiers.
- ❑ **We believe there should be a new science driver centered on flavor physics**, aiming at uncovering the physics behind the multifaced patterns of couplings, sources of CP violation and the mass scale and nature of the new physics, **with strong connections to the neutrino frontier**.
- ❑ **Many experimental approaches:** experiments investigating heavy and light quarks, charged leptons, precision tests of fundamental forces and symmetries, dark matter, and the dark sector.
- ❑ Support the **associated theory**, phenomenological and lattice QCD, which enables and inspires this experimental program

Our treasure hunt

- ❑ The origin of flavor, generations, and quark and lepton mass hierarchies
- ❑ The exploitation of flavor transitions as precision probes of all the sectors of the Standard Model and windows to new physics
- ❑ The motivation underlying discrete SM symmetries and mechanisms for symmetry breaking
- ❑ The origin of baryon and lepton number violation and connections to the baryon asymmetry of the universe
- ❑ Mapping of the wealth of conventional and exotic hadrons already discovered or in the horizon into organized multiplets of QCD bound systems

Our treasure map

A portfolio of accelerator dark sector experiments

Charged lepton flavor violation experiments

High-precision experiments with special focus on b and charm decays

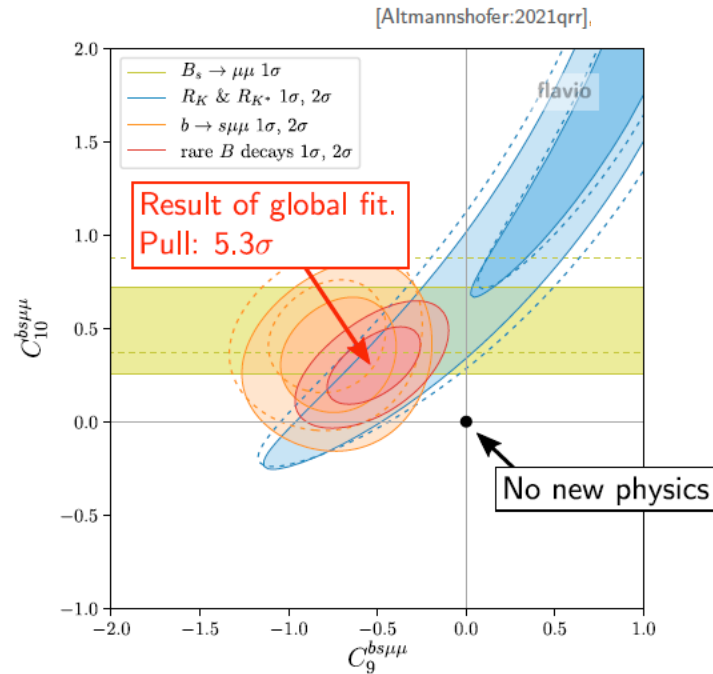
Experiments studying discrete & space-time symmetry breaking, electrical dipole moments & baryon/lepton number violation

- ❑ Phenomenological and lattice QDC theory efforts
- ❑ Innovations in instrumentation,
- ❑ Computing & accelerator physics

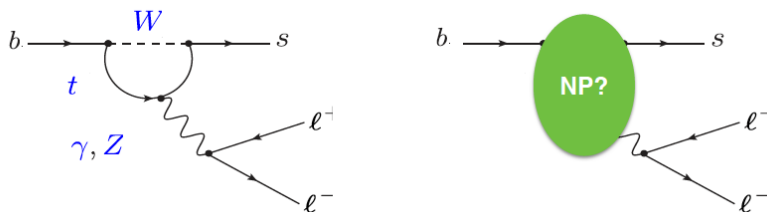
Disclaimer

- ❑ Attempt to capture a snapshot of the exciting physics we are proposing, I hope that you get a taste of the variety of exciting physics, a more complete and thoughtful picture will emerge in our report

Heavy flavor experiments: the next chapter

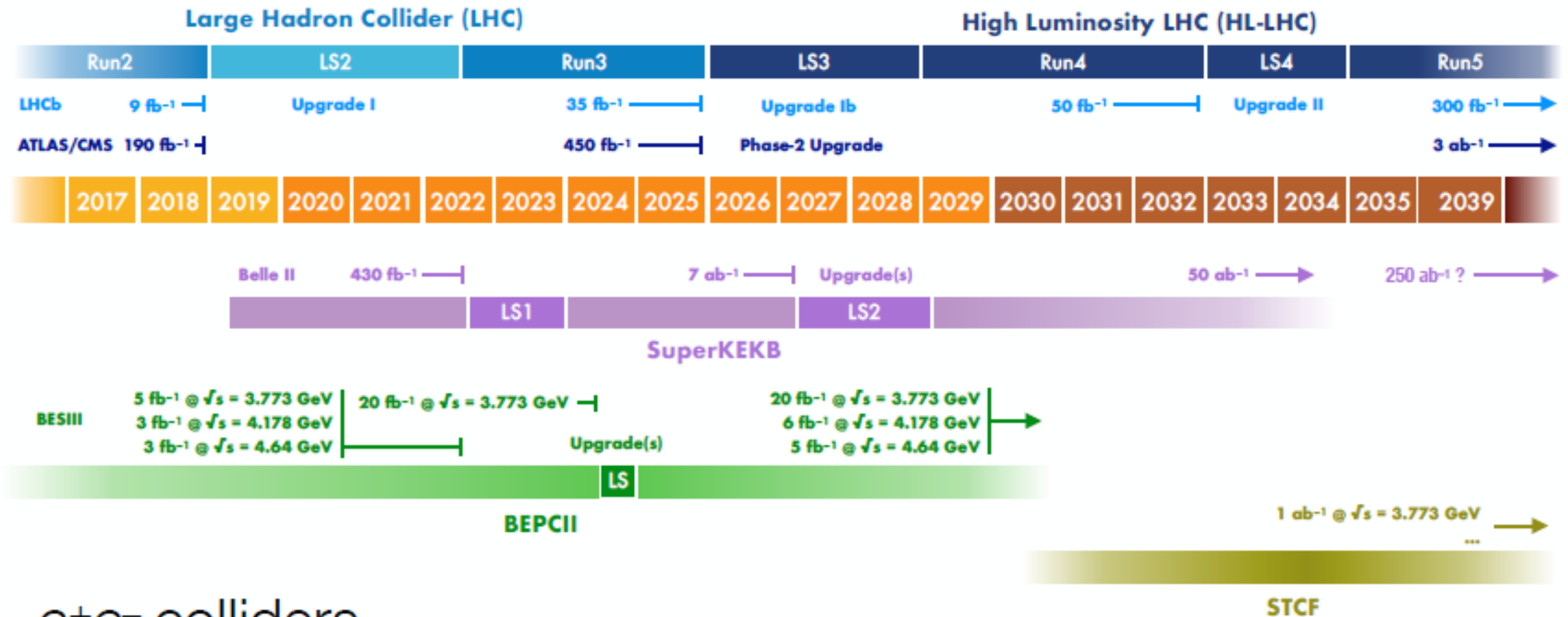


- ❑ Precision measurements of weak decays of heavy flavored hadrons can further our understanding of fundamental interaction and observed baryon asymmetry of the universe in a unique way
- ❑ Tantalizing hints of new physics are starting to emerge from measurements by the BaBar, Belle and LHCb experiments
- ❑ Next 10-20 years will see unprecedented development of a highly synergistic program of experiments at both pp and e+e- colliders, complemented and inspired by phenomenological and lattice QCD theoretical advances.



Heavy flavor experiments

hadron colliders



e^+e^- colliders

Exploring lepton flavor universality violation

<https://arxiv.org/abs/2204.12175>



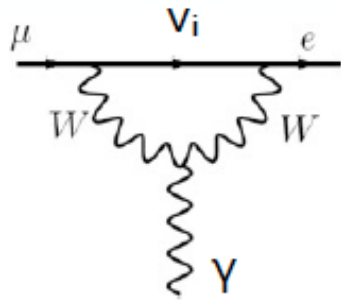
- ❑ Several tensions emerging
- ❑ Complementary studies in light meson decays
 - ❑ π decays to e and μ [PIONEER]
 - ❑ Rare η decays [REDTOP]

Precision tests of fundamental properties and symmetries

- Electric dipole moments (CP violation):
 - EDMs (besides QCD theta-term) instant discovery of new physics with energy scales up to 1000's TeV
 - Broad experimental approach due to a variety of possible CPV sources
 - HEP opportunity: storage ring proton EDM
- Magnetic dipole moments (focus on the muon):
 - Search for physics beyond the SM at the few TeV scale
 - Large theory effort in the next years to determine the hadronic contributions
- Precision experiments (HEP and AMO communities):
 - Search for fundamental symmetry violation (C, T, P, Lorentz, CPT)
 - Tests with gravity: fundamental symmetries, GR, quantum nature, short-range corrections
 - Wide set of low-energy approaches complementary to large-scale facilities

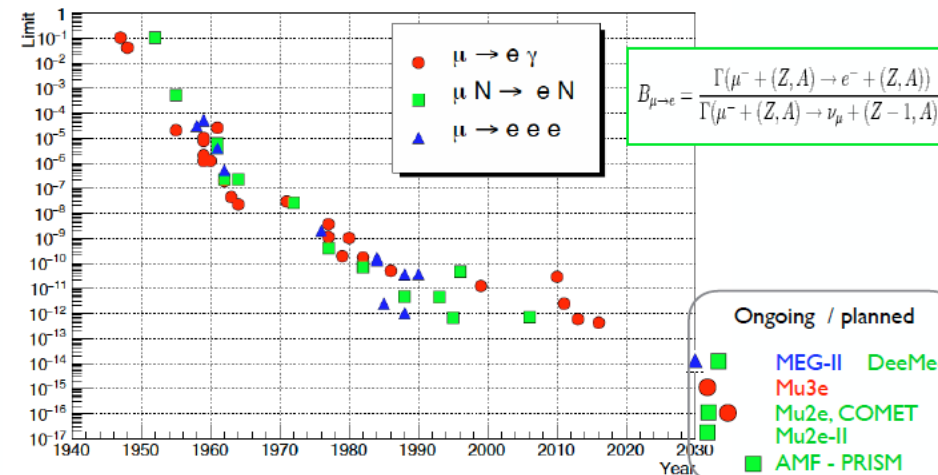
Charged lepton flavor violation

V. Cirigliano
colloquium

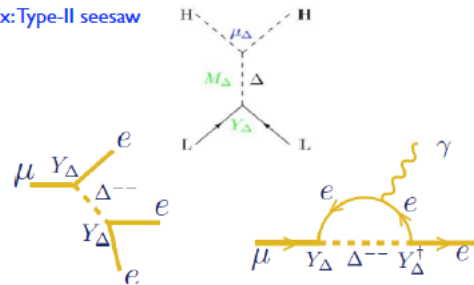


- Decays of μ , τ (and mesons)

$$\begin{aligned} \mu \rightarrow e\gamma, \quad \mu \rightarrow e\bar{e}e, \quad \mu(A, Z) \rightarrow e(A, Z) \quad M_\mu - \bar{M}_\mu \quad \mu \rightarrow ea \\ \tau \rightarrow \ell\gamma, \quad \tau \rightarrow \ell_\alpha \bar{\ell}_\beta \ell_\beta, \quad \tau \rightarrow \ell Y \quad Y = P, S, V, P\bar{P}, \dots \end{aligned}$$

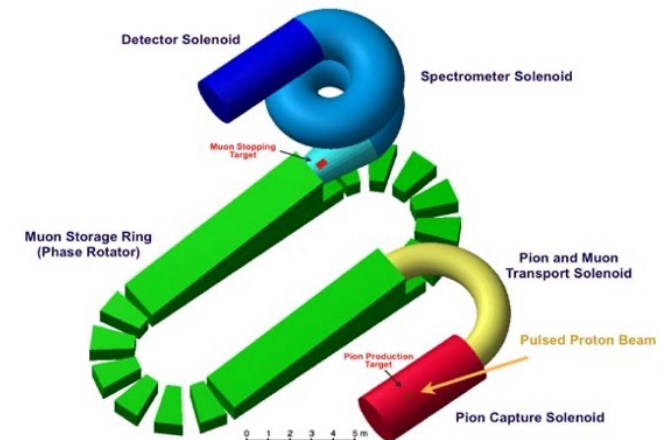


Ex: Type-II seesaw



Muon campus at Fermilab

- A new facility at FNAL could provide:
 - orders of magnitude increase in sensitivity for all three muon channels, $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, and $\mu N \rightarrow eN$ and open new possibilities in $\mu N \rightarrow eN$ at high Z
 - It can host a dark matter experiment + other muon measurements can be performed at this facility.
 - technical challenges are synergistic with the muon collider R&D



Dark sector

The existence of dark matter motivates a dark sector neutral under the SM forces

Dark sectors are a compelling possibility for new physics, with potential relevance to

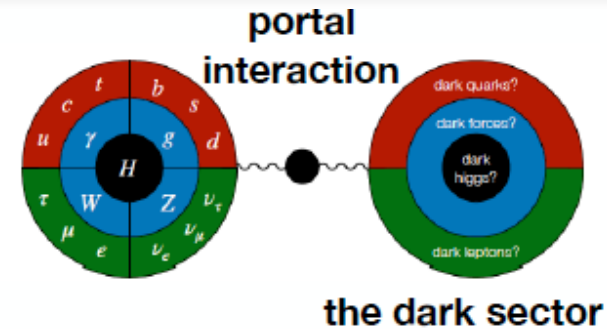
lightness of SM neutrinos, baryon-antibaryon asymmetry, hierarchy problem, strong-CP problem (e.g., axions, axion-like-particles), anomalies in data

Dark sectors are generically weakly coupled to SM matter (via portal interactions) and can naturally have MeV-to-GeV masses.

➔ Only mild constraints from precision atomic physics & high-energy colliders

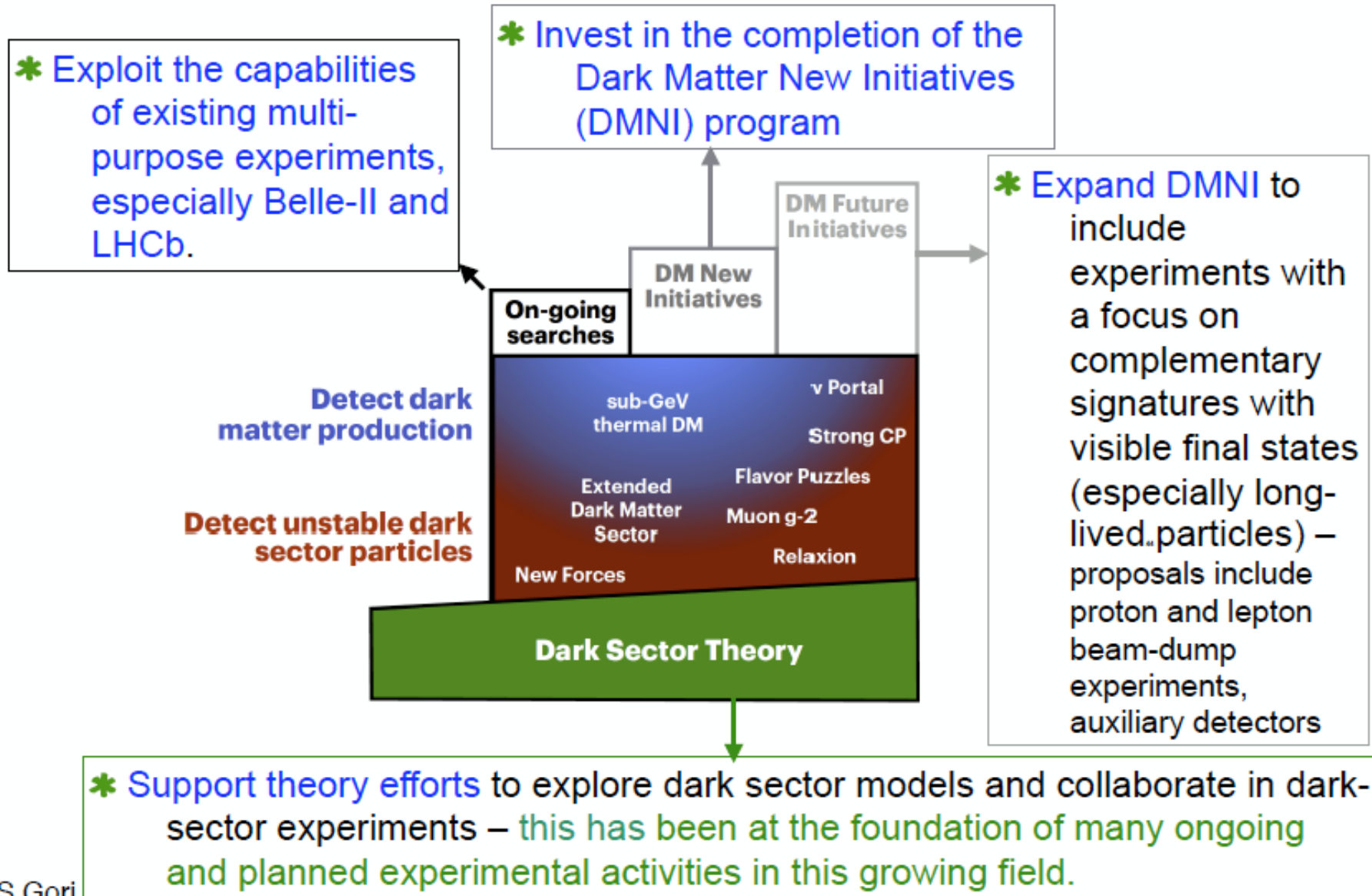
➔ Intensity-frontier experiments offer unique and unprecedented access to:

- Big idea 1 • Light dark matter production (focus on thermal dark matter)
- Big idea 2 • Systematic exploration of dark sector portal interactions
- Big idea 3 • Searches for new flavors and rich structures in dark sectors

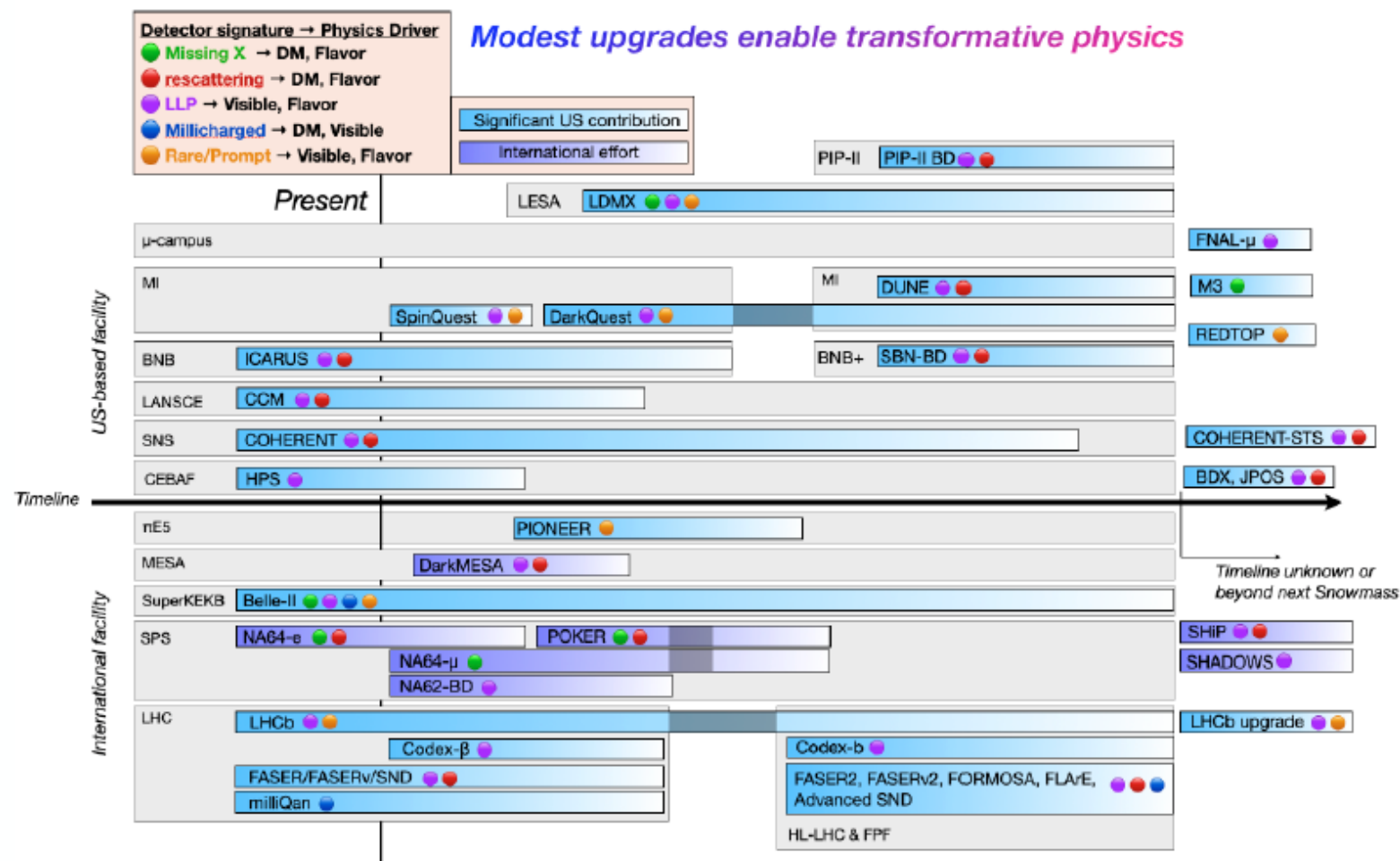


*Thanks to
S. Gori*

To promote US leadership in dark sector studies at high intensities:



Experiments/facilities



The RPF recommendations I

- ❑ The physics of our frontier **needs a new P5 driver** to be represented adequately in the HEP landscape, broadly identified as **physics of flavor**
- ❑ The **LHCb** and its **Upgrade II** and **Belle II/KEKB** and their upgrades are part of a portfolio of exciting physics opportunities that explore a vast array of **new physics** in beauty and charm decays, and in rare τ decays, In addition they investigate the pattern of bound states as manifestations of **QCD in the non-perturbative regime** and contribute significantly to the exploration of the **dark sector**.
- ❑ A portfolio of accelerator-based dark sector experiments that are well-motivate, unique and affordable should be considered.
- ❑ Experiments investigating **charged lepton flavor violation** and **lepton number violation** in the μ sector are integral components of our exploration of mass scales currently unreachable with direct detection.. R&D towards a new muon program at PIP-II should be given strong consideration to enable a concrete proposal for the next P5.

The RPF recommendations - II

- ❑ A portfolio of experiments of different cost and time scales are an integral part of our physics program. They include:
 - ❑ EDM measurement, including storage ring DM and experiments exploiting AMO techniques
 - ❑ Experiments leveraging on light mesons decays to uncover physics beyond the Standard Models, including anomalies and portals to the dark sectors [REDTOP, PIONEER]
 - ❑ Contributions to experimental studies of rare K decays should be encouraged
- ❑ We need to support theoretical efforts that inspire and elucidate the implications of our experimental findings

Concluding remarks

The six (?) -degrees of separation theory: **We are all connected!**

Instrumentation frontier: ps timing, DAQ, software trigger, massless trackers

Theory frontier: interpretation and inspiration

Energy frontier: direct searches for new physics

Connections with other communities: nuclear physics [e.g neutrinoless $\beta\beta$ Decay, AMO (EDM, fundamental symmetries..)]

Computational frontier: Massive data storage/processing, real time triggers/ distributed intelligence, ML

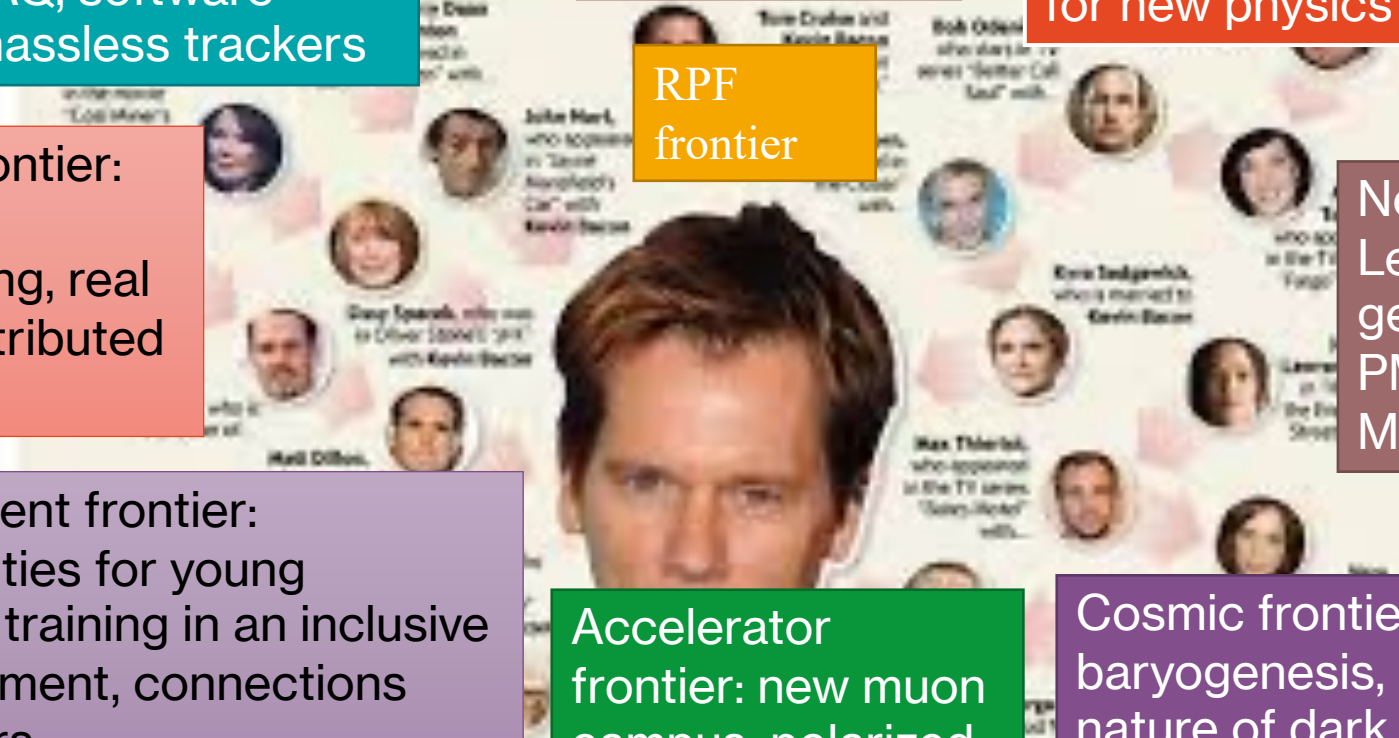
RPF frontier

Neutrino frontier: Leptogenesis/baryogenesis
PMNS versus CKM
Majorana or Dirac?

Community engagement frontier: Leadership opportunities for young scientist, attention to training in an inclusive and nurturing environment, connections with industrial partners

Accelerator frontier: new muon campus, polarized beams at KEK-b

Cosmic frontier: baryogenesis, the nature of dark matter





The end

Future prospects: two snashots

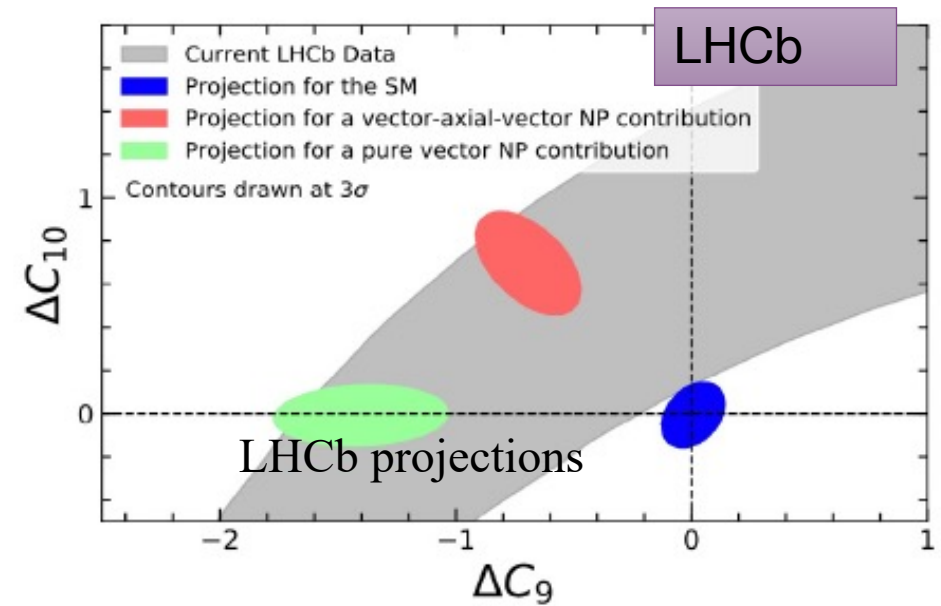
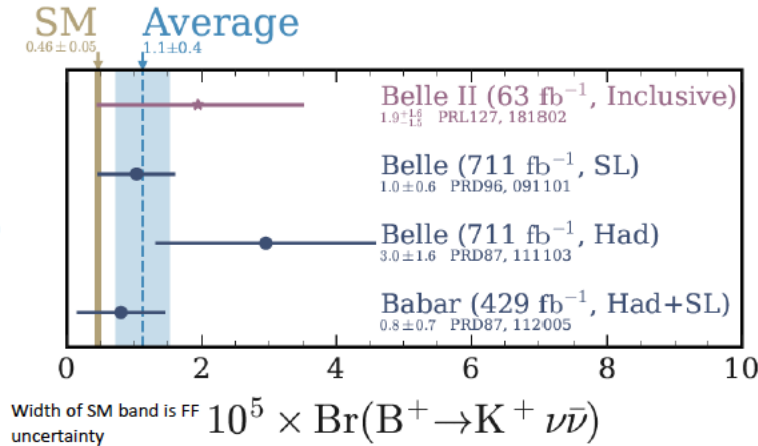
Belle II

$$B \rightarrow K \nu \bar{\nu}$$

New Technique from Belle II with inclusive ROE (Rest of the Event) tagging.

Phys. Rev. Lett. 127, 181802, (2021)

An emerging anomaly ???



4% experimental error on
 $B \rightarrow K^* \nu \bar{\nu}$ with 250 ab^{-1}

Integrated Luminosity	3 fb ⁻¹	23 fb ⁻¹	300 fb ⁻¹
<i>R_K</i> and <i>R_K</i> [*] measurements			
$\sigma(C_9)$	0.44	0.12	0.03
$\Lambda^{\text{tree generic}}$ [TeV]	40	80	155
$\Lambda^{\text{tree MFV}}$ [TeV]	8	16	31
$\Lambda^{\text{loop generic}}$ [TeV]	3	6	12
$\Lambda^{\text{loop MFV}}$ [TeV]	0.7	1.3	2.5
<i>B</i> ⁰ → <i>K</i> ^{*0} μ ⁺ μ ⁻ angular analysis			
$\sigma^{\text{stat}}(S_i)$	0.034–0.058	0.009–0.016	0.003–0.004
$\sigma(C'_{10})$	0.31	0.15	0.06
$\Lambda^{\text{tree generic}}$ [TeV]	50	75	115
$\Lambda^{\text{tree MFV}}$ [TeV]	10	15	23
$\Lambda^{\text{loop generic}}$ [TeV]	4	6	9
$\Lambda^{\text{loop MFV}}$ [TeV]	0.8	1.2	1.9